Remedy of "White Nights": A widely Applicable Light Pollution Evaluation System

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Abstract. Owing to the frequent presence of "white nights" recently, light pollution prevention and control measures are in great demand to resist the potential harm to humans and organisms. In this paper, we determined the light pollution risk evaluation index system from four dimensions to accurately measure light pollution risk levels in different types of areas. On this basis, the Revenue-Efficiency Index was introduced to measure sustainability. In response to the above analysis indicators, we proposed an advisable intervention strategy for glass curtain walls and confirmed its effectiveness through simulation. The indicator system was built by picking 40 countries with different levels of light radiation, and various indicators were chosen in multiple dimensions, thus the model is relatively reliable and universal.

Keywords: Light Pollution; Revenue-Efficiency Index; Topsis.

1. Introduction

Light pollution mainly refers to the excessive use of artificial light resulting in a variety of environmental, demographic, and ecological diversity with great harm, resulting in detriments mainly including glare pollution, circadian rhythm reversal, serious physiological diseases, and so on [1]. Therefore, research in the realm of evaluating the status of light pollution and inspiring how to reduce its severity is badly needed.

In 2021, Zhao et al proposed Maximum Light Pollution Indices and Accumulated Light Pollution Indices intending to assess glare and light trespass situations, together with over-illumination [2]. In the work of Yao et al, they tried to quantify the light pollution level of small-scale facade lighting displays and select Shenzhen street scene lighting situations for specific investigation [3]. With the development of satellite night light (NTL) images, researchers began to use satellite data to analyze light pollution and found that developed provinces (Hong Kong, Shanghai) had higher levels of light pollution than undeveloped provinces [4]. To analyze sources of light pollution, a city's point of interest (POI) data is collected and has been used to identify a city's commercial format and map population distribution [5].

Thus, in this article, we developed a model to assess the risk level of light pollution in four dimensions at various locations around the world and defined a specific metric to measure sustainability in the aspect of light conditions. To better solve the problem of light pollution, we also put forward a targeted measure, which is to change the coating material to reduce the light reflectivity. Through collecting concrete data of Heilongjiang Province and experiments, the result proves that this strategy is advisable.

2. Light Pollution Risk Evaluation Model

2.1. Light Pollution Risk Index

Reviewing the relevant literature, we believe that a region free of light pollution risk should have the following characteristics: stable circadian rhythm [6], balanced ecosystem [7-9], high quality of night sky observation [10], regular human activities [11], and sustainable energy use [12]. Therefore, in order to comprehensively and scientifically measure the light pollution risk status of a region, we subdivided four dimensions of energy consumption, environmental pollution, ecological impact, and human activities, and selected 13 secondary indicators to ensure the wide applicability of the model. The relationship between dimensions, indicators and influencing factors is shown in Table 1 below.

Table 1. Specific indicators table

Level 1	Level 2	Specific indicators	Units
Energy Consumption	EPC	Electric power consumption -world average	KWh per capita
Ecological Pollution	CO2	CO2 emissions	Metric tons per capita
	FC	Forest Coverage	Percentage of land area
	NOE	Nitrous oxide emissions	Metric tons per capita
Plant and Animal Impact	BT	Bird population diversity index	Percentage
	FT	Fish population diversity index	Percentage
	IV	Increase in vegetation in last 15 years	Percentage
Human Activities	PD	Population density	People per km^2 of area
	GDP	GDP per capita	US$
	IH	Intentional homicides	Per 100,000 people
	MCD	Mortality from CVD, cancer, diabetes or CRD between exact ages 30 and 70	Percentage
	MRT	Mortality caused by road traffic	Per 100,000 people
	NSL	Night sky level distribution	

What is worth mentioning is Night sky level distribution. The higher the zenith brightness is, the more serious the urban light pollution is, so the zenith brightness can be used as one of the important indicators to evaluate light pollution. This paper first classifies the regional sky brightness into four levels according to the number of observable stars, which corresponds to the population density of the region to further measure the degree of light pollution. Table 2 below lists the night sky levels and the effects of light pollution on astronomical observations.

Table 2. Night sky level and area division

The degree of contamination	level	Number of visible stars	Population density (number of people/km2)
pristine black sky, clouds appear black	4	7000	<1
2/3 of the stars are not visible, the clouds are visible	3	2400	1~25
sever light pollution	2	250	25~100
intense light pollution	1	25	>100

2.2. Light Pollution Risk Index

We chose EWM (Entropy Weighting Method) to objectively determine weights of second-level indicators, and then used AHP to score the first-level indicators comprehensively by referring to related literature.

Suppose we have a total of n countries with g first-level indicators. The jth level 1 indicator of sample country i has m level 2 indicators, and the value of the jth level 1 indicator after data processing is as follows, and the value of the kth level 2 indicator is x_{ik}.

$$\begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix} \tag{1}$$

The specific steps of model building are as follows:

2.2.1 EWM of secondary indicators

The entropy value e_j^k of the k-th second level indicator of the first level indicator j in the EWM of the second level indicator.

$$e_k^j = -\frac{\sum_{i=1}^{n} x_{ik} \ln x_{ik}}{\ln n} \tag{2}$$

A higher entropy value indicates that the secondary indicator k is more differentiated, contains more information, and should be given a higher weight. Then the information utility value is.

$$d_k^j = 1 - e_k^j \tag{3}$$

The weights w_k^j of the secondary index k are calculated as follows:

$$w_k^j = \frac{d_k^j}{\sum_{k=1}^{m} d_k^j} (k = 1,2,\cdots,m) \tag{4}$$

Then, we obtain the score of primary level indicator j considering the weights as:

$$y_{ij} = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix} \cdot \begin{bmatrix} w_1^j & \cdots & w_m^j \end{bmatrix}^T \tag{5}$$

Since our index system is divided into four dimensions, the EWM is applied to our data separately to calculate the weights of each dimensional indicator.

2.2.2 AHP for level 1 indicators

Next, we used AHP to determine weight values of the four dimensions, and the weight value vector is:

$$w = (0.2570,0.1325,0.5259,0.0846) \tag{6}$$

The overall description of light pollution risk level in a region is calculated by:

$$S = Y \times w^T \tag{7}$$

2.3. Revenue efficiency index

To further weigh the positive and negative effects of light pollution on a geographical area, we introduced the revenue efficiency index (RC), which specifically defines the positive effects of light pollution as:

$$IMP_p = PD + GDP \tag{8}$$

The negative effects of light pollution are:

$$IMP_n = EC + EP + PA + HA - IMP_p \tag{9}$$

RC is defined as the benefit-cost ratio:

$$RC_0 = \frac{IMP_p}{IMP_n} \tag{10}$$

$$RC = \frac{RC_0 - \min\{RC_0\}}{\max\{RC_0\} - \min\{RC_0\}} \tag{11}$$

This index indirectly reflects the conversion efficiency of the current benefits and costs incurred by humans owing to light pollution, and the larger it is, the greater the positive impact of light pollution. To determine the level of sustainability, we used a K-value clustering algorithm to find the thresholds, which divided the selected countries into four categories based on RC, and the thresholds are shown in Figure 3.

3. Results

3.1. Data pre-processing

For the specific data of secondary indicators needed to establish the model, we referred to domestic and overseas websites, such as the National Bureau of Statistics to query the population density of a specific area, GDP per capita, etc. We also used some public data shown in the OECD database, Avibase, and World Bank.

Data processing is necessary before the experiment, firstly we completed the missing values and excluded data with significant differences to avoid imbalance in weights. Furthermore, since different indicators have identified characteristics, we adopted different normalization methods for each type of indicator and standardized the mass of data.

3.2. Experimental results of evaluation model

Subsequently, we chose four typical countries, which are Tibet, Inner Mongolia, Heilongjiang and Shanghai to represent protected land, rural community, suburban community and urban community respectively.

After calculating correlations of each secondary index in the evaluation system with the brightness radiation of light, indexes with stronger correlation were selected as the specific index for further study. Figure 1 describes the association between secondary index and light pollution degree. It shows a non-linear, positive or negative relationship of them in four countries.

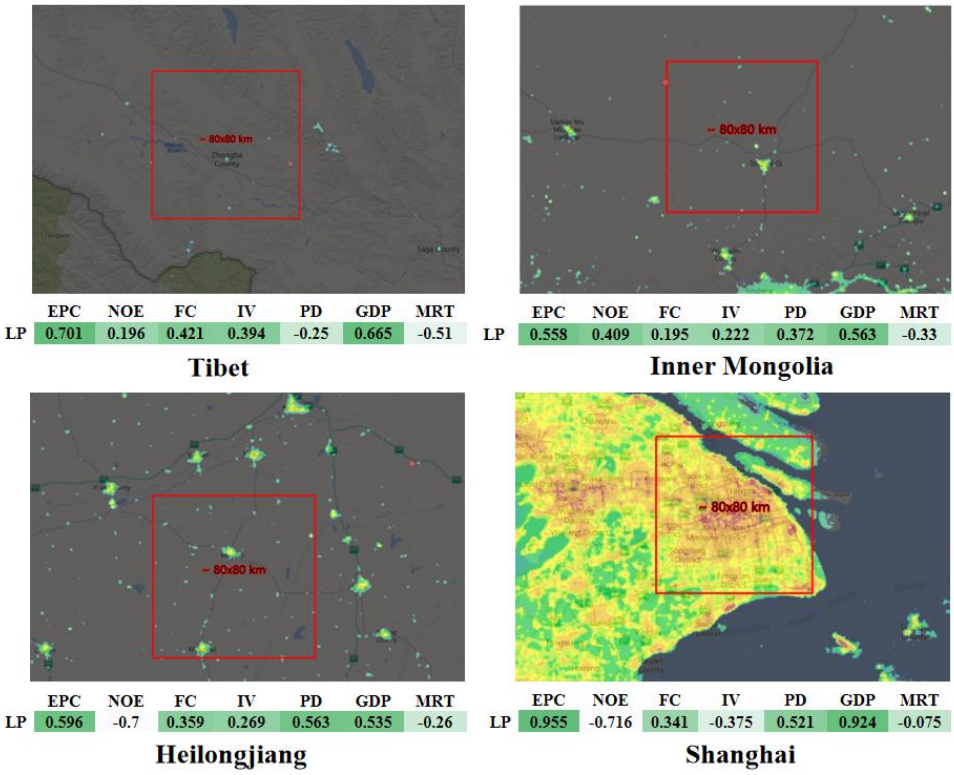


Figure 1. Comparison of optical radiation map and correlation coefficient matrix

Based on each secondary indexes, scores of primary indicators were figured up by category. For the Light Pollution Risk Index, the lower the score of each index, the better, the lower the score means that the region is less likely to be exposed to light pollution risk (Figure 2); while for the Revenue efficiency index (Figure 3), the larger the ratio, the better, i.e., light pollution generates more positive effects than negative ones.

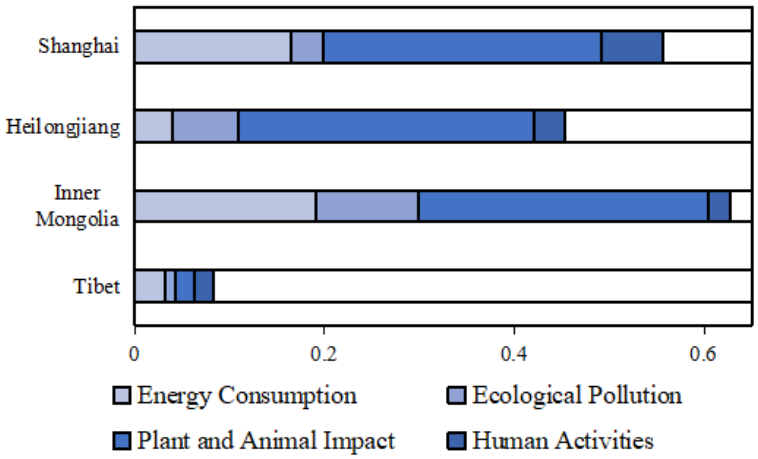


Figure 2. Light pollution risk level

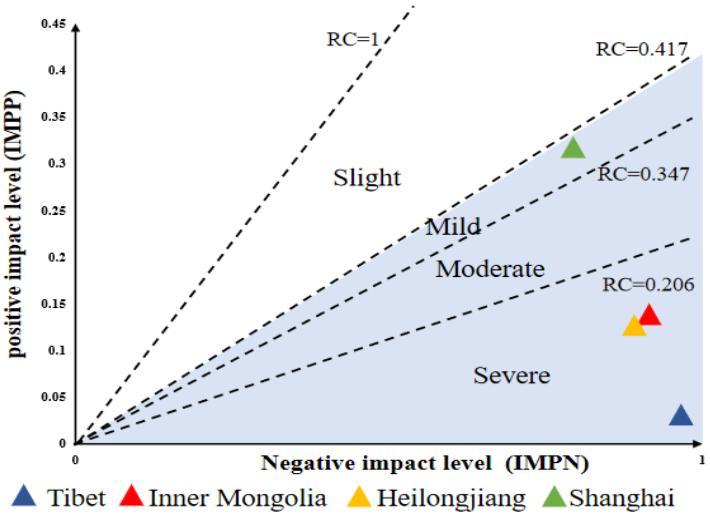


Figure 3. Revenue efficiency index and thresholds

3.3. Validation of targeted strategy's effectiveness

In general, the light reflection coefficient of white powder walls is 60% to 80%, the light reflection coefficient of mirrored glass is between 82% and 88% [13], while that of particularly smooth walls is up to 90%, which is about 10 times higher than that of surfaces decorated with grass or wool. It is already beyond the range of physiological adaptation and constitutes a new modern source of pollution [14].

For the prevention and control of reflected glare of glass curtain wall building, we adopted the way of coating to achieve by changing the coating material to reduce the light reflectivity and control the best diffuse reflection angle of 10%. The specific implementation is displayed in Figure 4 below.

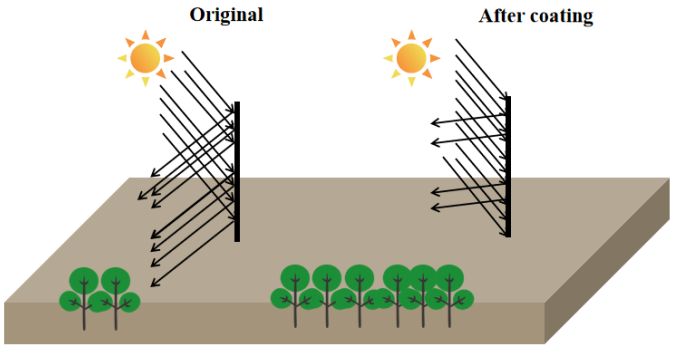


Figure 4. Change in reflection intensity before and after glass plating

From a biological point of view, the overload of photosynthetic processes in plants under intense light can lead to a decrease in the utilization of light quanta and photosynthetic yield [15]. To understand the effect of light intensity on plant growth, g is defined as the plant growth rate, p as the light intensity coefficient, x as the number of plants, and t as the daylight duration. Figure 5 shows the effect of light intensity on plant growth and plant growth rate would vary like the equation below:

$$g(p) = \frac{dx}{dt} = r_1 p^2 + r_2 p \tag{12}$$

In addition, glass curtain wall lighting is mainly realized by coating, the coating would absorb part of the strong light, and the plant growth rate g becomes larger as time increases; at the same time, it will make the light radiation intensity decrease to 1.1 times of the original, which makes g near the optimal point, that is, located at the light saturation point (Figure 6), in order to improve the plant coverage, thus affecting the BT index value.

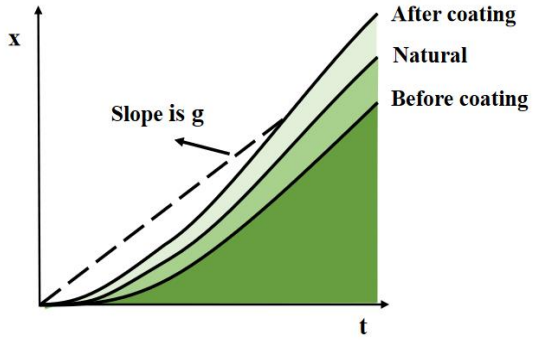


Figure 5. Variation of plant growth rate in relation to coating

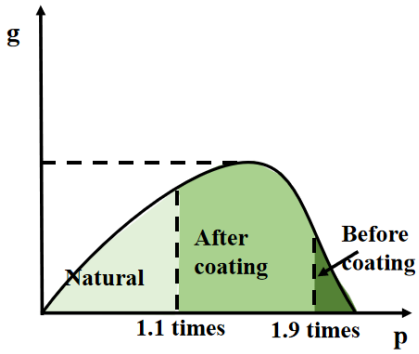


Figure 6. Trend of plant growth rate

Heilongjiang is a suburban area, whose biodiversity is more easily affected by light pollution. After implementing the coated glass, PA was controlled substantially, shown through Figure 7. This may be due to most of the organisms living in the suburbs depend on vegetation, and the reduction of glass glare can increase plant coverage, which in turn provides more space for organisms living in the suburbs to survive.

Additionally, Figure 8 elaborates that Heilongjiang would benefit significantly owing to the strategy and become more stable in general, transitioning from severe to moderate state.

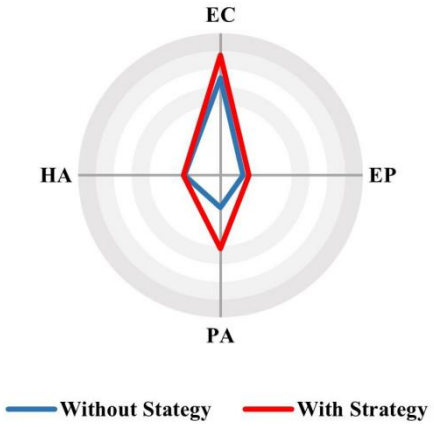


Figure 7. Change in light pollution risk index

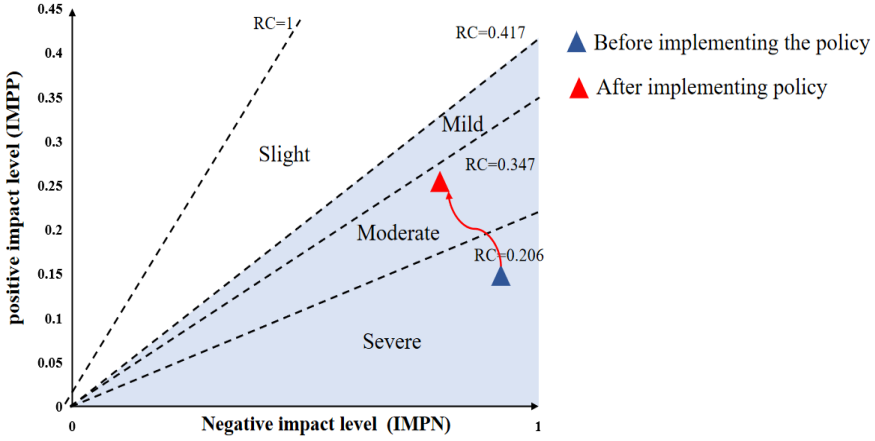


Figure 8. Change in revenue efficiency index

4. Conclusions

The aim of our research is to establish an applicable model to assess the risk level of light pollution objectively and measure each district's sustainability. We built the evaluation system considering 40 countries with different levels of light radiation and various indicators in multiple dimensions. Thus, the model can act as an inspiration to better tutor how to curb light pollution in different variety of regions. Based on statistics and research, we proposed changing the coating material to reduce the light reflectivity. This novel method would increase plant growth rate to the optimal point, thus enhancing local ecological condition, and it is particularly expedient in areas with abundant biodiversity.

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